LOFAR Scientific Memorandum #4
LOFAR and Gravitational Lenses

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I consider the use of LOFAR for the discovery of a large number of new gravitational lenses. An all-sky, relatively shallow survey (rms $\sim 20\,\mu$Jy) is shown to contain 35 million sources suitable for conventional gravitational lens survey techniques. We could expect to detect at least 17000 new multiple-image gravitational lens systems from such a survey (cf. the current number of 60–70) which would provide major advances in our understanding of mass models of galaxies and galaxy evolution. There are serious detection issues, in the fraction of lenses which would be recognised but mainly in the number of false positive detections which make confirmation of lens systems impossible if they vastly outnumber true lenses. Resolution will be critical for both of these criteria.

1 Introduction: uses of gravitational lenses

Multiple-image gravitational lenses produced by a galaxy along the line of sight to a background object are interesting for a number of reasons. In some cases, where the number of model constraints is high enough, they can provide very detailed mass models of the lensing galaxy independent of its light distribution (Cohn et al. 2001; Wucknitz 2002). It has been known for some time that the total number of lenses found in a well-selected survey is sensitive to cosmological parameters, in particular to the cosmological constant (Fukugita et al. 1992; Kochanek 1996), and if the cosmological parameters are known the lens statistics become an important probe of galaxy evolution as a function of mass (Chae 2002).

Searches for gravitational lenses rely on the brute-force strategy of observing large number of background objects at cosmological redshifts to find the one-in-600 lucky chance of an intervening galaxy which lies close enough to produce multiple-image gravitational lensing. The CLASS survey, just completed, has produced 22 lenses from 16560 observed sources. Here I discuss the prospects for LOFAR, which will find hundreds of millions of radio sources in a typical survey. I discuss the type of survey which would be required to detect lenses and the number of sources found, calculate the number of lenses which would be likely to be detected, consider the proportion of these lenses which could be detected by LOFAR, and discuss the observational problems associated with separation of the true lenses from false-positive candidates.

2 Basic parameters of a likely LOFAR survey

I assume that two months is spent on a wide-area survey at one or more of LOFAR's higher frequencies ($\geq$ 150MHz). Such a survey could cover 600 pointings of $30^{\square}$ each, or about 2π sr; at about 2.4 hours per pointing the rms noise level would be about 18μJy, assuming a noise of 2.4mJy/s/4MHz and a bandwidth of 8MHz. Such a survey at arcsecond resolution would be an excellent resource for all kinds of science. Here I focus on the opportunities for gravitational lensing.

3 Number of sources found

Sources would be detected at 70μJy (4σ) in such a survey. For lensing investigations the ideal signal-to-noise is about 35:1, as typically secondary images of flux levels about one-tenth of the primary must be detectable. Hence the practical limit for lenses in such a survey would be about 0.7mJy.

The source count at 151 MHz is approximately 17000 sr^{-1} ($5/^{\square}$) to a limiting flux of 200 mJy (McGilchrist 1999). Assuming a canonical integral source-count slope of -1 gives about 5×10^{6}sr^{-1} to 0.7mJy, or about $1500/^{\square}$. There would be $15000/^{\square}$ sources actually detected to the survey limit of 70μJy.

We can also extrapolate from the results of deep radio searches in the HDF. Richards et al. (1998) find about $1600/^{\square}$ to 9μJy at 8.4 GHz, and hence about $200/^{\square}$ are likely to 70μJy at this frequency. At 1.4 GHz Muxlow et al. find $3100/^{\square}$ to 40μJy and hence about $1700/^{\square}$ to 70μJy. Extrapolating to 151MHz leads us to expect about $17000/^{\square}$ to this flux density level.

We can therefore conclude that about 350 million sources would be found in a 2π-sr survey, of which 35 million would be strong enough to be investigated for the effects of multiple-image lensing. It's worth noting, however, that some of the 350 million sources could be detected as lenses if smeared into Einstein ring or arc structures.

4 What do we know about these sources?

The sources being investigated for lensing would be the 35 million sources with flux densities >0.7mJy at 151 MHz. The vast majority of these correspond to the population with flux densities of 70μJy or more at 1.4 GHz, exactly the population imaged in the HDF by Richards et al. and Muxlow et al. A lot is already known about the properties of this population. It is a predominantly steep spectrum population, whose radio structures are nearly all on scales of $0''.5$-$2''$, and whose median redshift is approximately 0.7, although a substantial (>10%) fraction of the population probably lies at redshifts of 2 or greater. About 20% of the population are AGN-type with radio cores or other compact and probably flat-spectrum structure. The remainder are starbursts, a substantial proportion of which may lie at high redshift and/or be dust-enshrouded given the lack of obvious optical identification.

5 What would the lensing rate be?

The lensing rate in a given population of background radio sources is dependent on:

- the number density and evolution of the population of lensing galaxies
- the redshift distribution of the radio sources
- the source-count slope (as lensing magnifies a background source, most of the lenses' intrinsic flux densities lie just below the survey flux density cutoff)
- the cosmological parameters Ω_m and Ω_Λ.

In most surveys at higher flux density levels, such as the CLASS survey, the lensing rate is approximately 1:600. CLASS reached a flux density limit of 30mJy at 5GHz and contained mostly flat-spectrum sources. Depending on radio spectra, a LOFAR survey will reach flux density levels 50 to 2000 times fainter.

In the fainter survey, three of the parameters (cosmology, lensing galaxy distribution and source-count slope) affecting lensing rate are unchanged. In particular, the $N(>S)$ slope appears to be about -1 at CLASS survey flux density levels and at fainter levels. The only possible effect on lensing rate would occur if the source population picked up by LOFAR were of substantially lower redshift than the CLASS sources. As has already been argued, we have a very good idea of what the LOFAR population would look like; it would be essentially the same as the HDF 10-50μJy population, the redshift distribution of which is known (Richards et al. 1998) and where the few unknown redshifts can be guessed fairly well from the infrared K-band fluxes. Proceeding on this basis, a simulation has been run by K.H. Chae using the same code used to infer cosmological parameters from the lensing rate in the CLASS survey, but in reverse; the cosmological parameters have been assumed (Ω_m=0.3, Ω_Λ=0.7) and the redshift distribution of Richards et al. used to calculate a lensing rate. The result is 1:2000 leading to a total number of 170000 lenses in the entire (350-million source) sample, or 17000 in the brighter survey where 30σ signal-to-noise allows investigation of lens candidates with 10:1 primary-to-secondary flux density ratios.

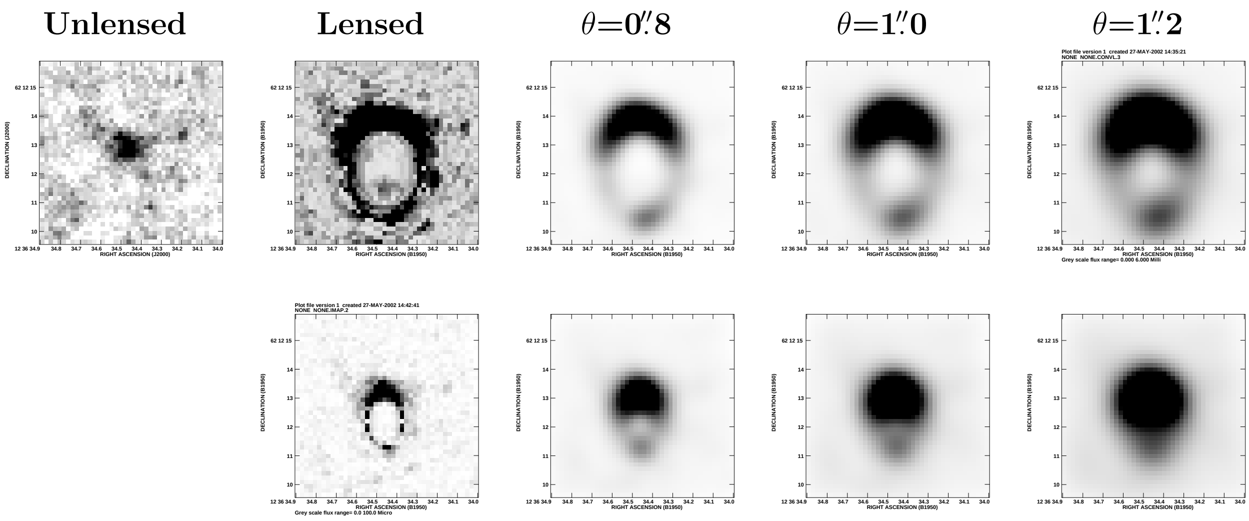

Figure 1: The source HDF J123634+6212 (Muxlow et al. 2001) lensed by an object with (top row) Einstein radius $1''.5$ and (bottom row) a more typical object with Einstein radius $0''.7$. The resulting lensed image is shown for three different restoring beams between $0''.8$ and $1''.2$.

6 Detection issues: some pictures

The source J123634+6212 is a fairly typical source from the HDF Merlin/VLA survey (Muxlow et al. 2001) with a size of $\sim 0''.7$. (Nearly all such sources are resolved, with sizes between $0''.5$ and $2''$). Figure 1 shows the unlensed source, and also shows the source as it would be observed if lensed by foreground sources with Einstein radii of $1''.5$ and $0''.7$. The larger lens corresponds to the upper envelope of galaxy mass distributions from the CLASS survey lenses, and the smaller lens to the typical median sie of such lenses. The lensed images are also shown convolved with restoring beams in the likely LOFAR range of $0''.8$ to $1''.2$. Not surprisingly, the difference between the sizes of the restoring beam is critical; the typical lens of $0''.7$ scale would emerge as a clear candidate with $0''.8$ resolution but be impossible to spot as lensed (arc-like) rather than intrinsic structure if a larger beam were used.

7 Detection issues: simulations from CLASS and proportion of lenses found

Augusto & Wilkinson (2001) performed extensive simulations as part of the CLASS survey to determine the smallest possible separation as a function of restoring beam at which lenses could be identified. They found that lenses with primary-to-secondary flux ratios of 7:1 could be reliably identified provided that the separation was at least 160 mas, compared to the 220-mas restoring beam of the CLASS observations. This would suggest that a $0''.7$ lens could be

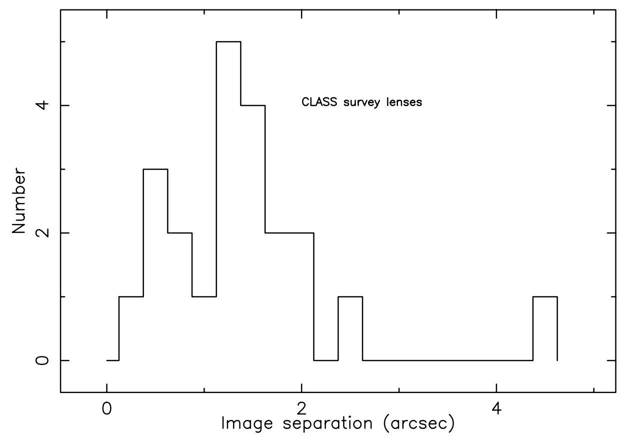

Figure 2: CLASS survey lens separations (Myers et al. 2002; Browne et al. 2002)

reliably found if the LOFAR resolution were $1''$ or better. However, for current purposes, their simulations are optimistic for two reasons.

- The simulations were performed on the brighter objects within the CLASS sample and assumed that the signal-to-noise was high. This is unlikely to be the case for the faint objects that would dominate a LOFAR survey. Note that Fig. 1 essentially assumes high signal-to-noise, as the lens magnification ensures that the lensed images are very bright relative to the noise level.
- The simulations assumed point objects. The 50-μJy source population itself consists of extended objects.

The first point was addressed in further simulations by Naisbit (2001). He found that automatic selection was able to find lenses reliably only for separations greater than about 90% of the beam FWHM, when noise was added to simulations to give approximately 40:1 signal-to-noise in the primary component. The second point is more difficult to address directly, but inspection of Fig. 1 suggests that Naisbit's criterion should be adopted as a basic minimum requirement for the detection of lenses.

The histogram of lens separations from the CLASS survey is shown in Figure 2 (Myers et al. 2002; Browne et al. 2002). Note that this survey is believed to be essentially complete to $0\farcs2$ separation. On the face of it, this is good news; it implies that in principle, over 60% of lenses could be found by the canonical LOFAR array with $1''$ resolution. However, the feasibility of a lens survey depends not only on the fraction of true lenses identified as such, but on the fraction of non-lensed sources flagged as possible lenses (false positives).

8 Detection issues: false positives

The difficult part of a lens survey is the separation of the true lenses from a number of lens candidates. In the CLASS survey, 16560 sources were observed, and about 300 candidate lenses were selected which had non-pointlike structure visible on $0\farcs2$-resolution maps. 22 lenses resulted from this process. The remaining sources were rejected as lens candidates, usually because they consisted of an unresolved primary and secondary structure which, being resolved on higher-resolution MERLIN and VLBA maps, could not be lensed images of the primary.

The LOFAR case is more difficult for two major reasons. First, the resolution is almost certainly going to be worse by a factor of $\sim$4 than the primary CLASS finding survey. Second, the background sources are not going to be point radio sources, as was the case for the CLASS survey which targeted flat-spectrum and predominantly pointlike radio sources. Moreover, identification of the CLASS lenses took about 100 person-years of effort and involved looking through all 16560 radio maps individually, a task that is obviously impossible with a sample of 35 million.

Let us try to quantify the above discussion. We start with a sample of 35 million radio sources, and assume a survey with $1\farcs0$ resolution. This allows us to attempt identification of lenses with separations of about $0\farcs9$ or greater, given signal-to-noise constraints discussed earlier. Since the lensing rate is approximately 1 in 2000 and since about 60% of lenses have separations greater than this, we would expect to find about 12000 lenses. However, if we follow the CLASS procedure and consider any source with resolved structure as a lens candidate, we can see from the angular size distribution in the HDF radio sources (Fig. 1 of Muxlow et al. 2001) that the 12000 genuine lenses are accompanied by about 20 million false positives, as about 60% of HDF radio sources have angular sizes greater than $1''$.

Simply detecting the lenses with LOFAR is easy; the requirements for any LOFAR survey parameters are therefore dominated by the need to avoid unfeasibly large numbers of false positive detections which will make followup prohibitive. *The resolution has to be high enough that lenses can be separated on morphological grounds alone.* Fortunately, the fact that nearly all HDF radio sources are significantly extended has the redeeming feature that nearly all lenses found by the LOFAR survey should show evidence for arc structure. *The lenses detected in the LOFAR survey will not be detected by multiple imaging, as has been done in previous surveys, but by identification of arc-like structures.* The human eye does this very well, but for 35 million sources more sophisticated algorithms will be required, almost inevitably involving the use of trainable algorithms such as neural networks. Much more sophisticated simulations will need to be done to assess completeness of these detections. Unfortunately, these will only be possible once the major LOFAR survey of the parent population is actually under way, as we do not yet have an idea of the range of structures present in large samples of radio sources at this low flux level.

The basic observational point is that *resolution needs to be higher* for the detection of arcs than for the separation of multiple components. Essentially, the arcs themselves need to be resolved; a beam of about 0.4 of the lens separation is needed rather than the 0.9 for multiple-image component separation. In order to detect significant numbers of lenses – say about half the population – this requires LOFAR's resolution to be about $0\overset{''}{.}5$. $1''$ resolution will not be efficient at detecting any but the very largest lensing masses ($10^{13}M_\odot$), and of those only the four-image lenses will be detected as the arc-criterion will probably not be usable at this resolution. There will be a very steep slope in science gain with resolution in between these limiting cases.

9 Summary: detection, resolution, and relation to science drivers

Because of its ability to detect vast numbers of sources, LOFAR has the ability to detect several hundred times more gravitational lenses than are currently known, resulting in systems allowing us to determine mass models with exquisite precision in the best cases and to constrain galaxy evolution. Because of the extended nature of the lensed population of sources, the demands on the instrument for lens-finding algorithms are correspondingly greater. To be an efficient lens-finding machine, and impact more than slightly on the research area, it is highly desirable that the resolution of LOFAR should be substantially less than $1''$ at the highest frequency of operation, and ideally $0\overset{''}{.}5$.

There is almost no chance that a LOFAR survey will be complete in the sense that all lenses will be discovered; this would require unfeasibly long baselines and resolutions of 50-100mas. There is therefore no chance that a LOFAR survey will contribute to determination of cosmological parameters. However, given the timescale of development of LOFAR compared to other instruments such as Planck and other CMB space missions, it is likely that cosmological parameter determination will not be a major science driver five to ten years hence.

However, one can expect that a LOFAR survey will be reasonably complete in the large-separation range, provided that its basic resolution is sufficiently ($0\overset{''}{.}5$ – $0\overset{''}{.}7$) high. This will enable substantial progress to be made in constraints on galaxy evolution models. The main contribution will be a large number of lenses which will allow galaxy mass modelling and detailed determination of mass distributions of galaxies at cosmological redshift.

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